

Possible Evidence For Axino Dark Matter In The Galactic Bulge

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Recently, the SPI spectrometer on the INTEGRAL satellite observed strong 511 keV line emission from the galactic bulge. Although the angular distribution (spherically symmetric with width of $\sim 9^\circ$) of this emission is difficult to account for with traditional astrophysical scenarios, light dark matter particles could account for the observation. In this letter, we consider the possibility that decaying axinos in an R-parity violating model of supersymmetry may be the source of this emission. We find that $\sim 1 - 300$ MeV axinos with R-parity violating couplings can naturally produce the observed emission.

95.35.+d, 14.80.Ly, 07.85.Fv, 14.80.Mz

I. INTRODUCTION

The SPI spectrometer on the INTEGRAL (International Gamma-Ray Astrophysics Laboratory) satellite has made the observation of a bright ($9.9^{+4.7}_{-2.1} \times 10^{-4} \text{ ph cm}^{-2} \text{ s}^{-1}$), 511 keV gamma-ray emission line from the galactic bulge [1]. The emission is consistent with being spherically symmetric, with a full-width-half-maximum of about 9° ($6^\circ - 18^\circ$ at 2σ confidence). The 3 keV width of the line is dominated by $e + e^-$ annihilations via positronium formation [2]. These findings are in agreement with earlier observations, such as those by the OSSE experiment [3].

This observation of bright 511 keV emission from the galactic bulge has been quite difficult to explain with traditional astrophysics. Most potential sources considered do not produce a sufficient number of positrons (such as neutron stars, black holes [4], radioactive nuclei from supernovae, novae, red giants or Wolf-Rayet stars [5], cosmic ray interactions with the interstellar medium [6], pulsars [7] or stellar flares) and those which may possibly be capable of producing the required number (type Ia supernovae [8,9] or hypernovae [10,9]), may not be capable of filling the entire galactic bulge [11]. In particular, the rate at high altitude is likely to be too low to explain the observed extension of the 511 keV source [12].

Given this difficulty, alternative explanations should be considered. In Ref. [13], it was suggested that light (1-100 MeV) dark matter particles annihilating in the galactic bulge could explain the observed emission. In this letter we, instead, consider light *decaying* dark matter particles. In particular, we consider the supersymmetric partner of the axion [14], the axino, in R-parity violating supersymmetric models.

In the Minimal Supersymmetric Standard Model (MSSM), a Z_2 symmetry, R-parity [15], is usually imposed to forbid dimension four operators which lead to fast proton decay [16]. A by-product of an exact R-parity is that the Lightest Supersymmetric Particle (LSP) is stable and often a good candidate for cold dark mat-

ter. Although R-parity is an elegant way of suppressing proton decay, it does not have to be the only way that nature can choose to do so. In particular, baryon parity is sufficient to make the proton stable. In this case, the coupling strengths of other R-parity violating operators, such as $\lambda_{ijk} L_i L_j E_k^c$, are much less constrained. For a summary of R-parity violating coupling constraints, see Ref. [17].

A typical dark matter candidate provided by R-parity conserving supersymmetry is a neutralino LSP. Neutralinos are the superpartners of the neutral gauge bosons and Higgs bosons and have masses constrained by direct searches to be greater than ~ 30 GeV, too heavy to produce a large flux of thermal positrons. Of course, with sizable R-parity violation, the neutralino will have a short lifetime and cease to be a good candidate for cold dark matter.

With the Peccei-Quinn (PQ) mechanism [14] providing a natural solution to the strong-CP problem in a supersymmetric theory, the existence of an axino is inevitable. The axino's mass is expected to be considerably lower than the electroweak scale, perhaps in the keV to several GeV range and is capable of providing the observed quantity of dark matter given a low reheating temperature [18–22]. Since the axino is in the same supermultiplet as the axion, its couplings to matter fields are generically suppressed by f_a^{-1} , where f_a is the PQ symmetry breaking scale $\sim 10^9 - 10^{12}$ GeV. As we shall see in detail in this paper, due to this large suppression, axinos could be considered *stable* during the history of the universe even in the presence of sizable R-parity violating couplings. Furthermore, a long-lived MeV-GeV axino, such as we consider in this letter, would be heavy enough to constitute a good candidate for cold dark matter [21–23].

A possible concern for axinos in the early universe is their effect on the light element abundances [24–26]. With a long-lived axino, however, axino decays do not threaten these observations. Furthermore, with the introduction of R-parity violation in our scenario, we allow for relatively fast Next-to-Lightest Supersymmetric

Particle (NLSP) decays into Standard Model particles. Thus the epoch of SUSY particle decays is over prior to nucleosynthesis and the light element abundances remain unaffected [27].

Before going into a more detailed study of decaying axinos, we briefly consider here the possibility of decaying gravitinos. Gravitinos also have highly suppressed couplings to matter (M_P^{-1} in the kinematical regime of interest) and could be a good candidate for cold dark matter. We have found, however, that for the case of trilinear R-parity violating terms, the gravitino lifetime is too long to account for the observed 511 keV emission (see section II). In particular, the gravitino lifetime is estimated to be $\tau_{3/2} \sim 10^{31} \text{ sec } (m_{\tilde{l}}/100 \text{ GeV})^4 (0.1 \text{ GeV}/m_{3/2})^7 (0.1/\lambda)^2$.

II. DECAYING DARK MATTER

If light dark matter particles constitute the galactic halo, decays of such particles can produce positrons which eventually annihilate producing the observed 511 keV emission. In this section, we calculate the lifetime of a light decaying dark matter particle needed to account for the observed 511 keV flux.

We note that although the observed emission line is energetically narrow, indicative of positrons annihilating at rest, positrons resulting from dark matter decays need not be at rest, as they will stop easily via ionization losses before annihilating as long as their initial energy is less than $\sim 100 \text{ MeV}$ [13]. This energy corresponds to decaying dark matter particles of a few hundred MeV or less.

The dark matter distribution in the galactic halo is traditionally parameterized by

$$\rho(r) \propto \frac{1}{(r/a)^\gamma [1 + (r/a)^\gamma]^{(\beta-\gamma)/\alpha}}, \quad (1)$$

where α , β and γ are given by the choice of halo profile and a is the distance from the galactic center at which the inner power law breaks. In the galactic bulge, $r \ll a$, and the parameterization reduces to $\rho(r) \propto \frac{1}{(r/a)^\gamma}$. Integrating over the line-of-sight of the observation, and averaging over the angular resolution of SPI ($\sim 2^\circ$), the angular distribution of 511 keV gamma-rays from dark matter decays for a given halo profile can be compared to the observations of SPI/INTEGRAL. In figure 1, we show these results. We find that for a cusped profile, $\gamma \simeq 1.2$, the data is well fitted. This is in agreement with the results of recent high resolution N-body simulations [28]. Note that in Ref. [13], the best fit was found for $\gamma \simeq 0.6$. This is because for annihilating dark matter, the annihilation rate is proportional to the density squared, rather than simply the density.

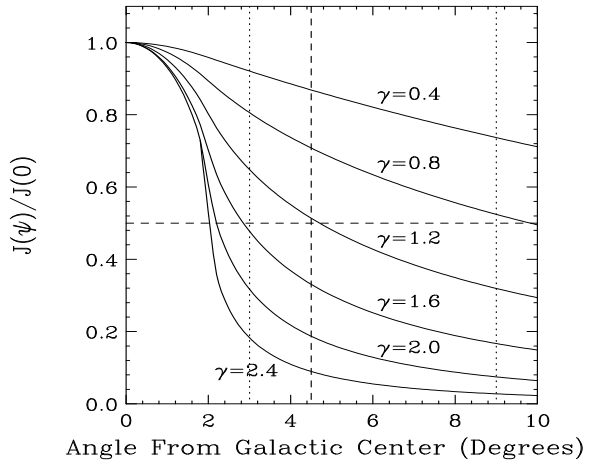


FIG. 1. The angular distribution of 511 keV γ -rays from decaying dark matter averaged over the 2° angular resolution of the SPI spectrometer on INTEGRAL for several halo profiles. SPI's observation indicates a full width half maximum of 9° with a $6^\circ - 18^\circ$ 2σ confidence interval. Shown as vertical dashed and dotted lines are the central value and 2σ limits of the angular widths found by SPI. To agree with this data, a cusped halo model with $\gamma \sim 0.8-1.5$ is favored.

Normalizing the halo profile to the local dark matter density, we obtain

$$\rho(r) \simeq \frac{0.3 \text{ M}_\odot/\text{pc}^3}{(r/1 \text{ kpc})^\gamma}, \quad (2)$$

where $\gamma \simeq 1.2$. The total mass within the 9° circle observed by INTEGRAL is then

$$M = \int_0^{670 \text{ pc}} \rho(r) 4\pi r^2 dr \simeq 1 \times 10^9 \text{ M}_\odot \cong 1.5 \times 10^{66} \text{ GeV}. \quad (3)$$

The rate at which dark matter decays in this region is simply the total mass divided by the mass and lifetime of the dark matter particle. Also, the rate of decays can be matched to the observed flux of 511 keV gamma-rays. Comparing these two quantities yields

$$\frac{1.5 \times 10^{66} \text{ GeV}}{m_{\text{dm}} \tau_{\text{dm}}} \sim \frac{1}{2} \Phi_{\gamma,511} 4\pi R_{\text{GC}}^2. \quad (4)$$

Here, $\Phi_{\gamma,511}$ is the observed 511 keV gamma-ray flux and R_{GC} is the distance of the Earth from the galactic center. Inserting the observed flux ($\Phi_{\gamma,511} \simeq 10^{-3} \text{ ph/cm}^2\text{s}$) and $R_{\text{GC}} \simeq 2.5 \times 10^{22} \text{ cm}$, we arrive at

$$\tau_{\text{dm}} \sim 4 \times 10^{26} \text{ seconds}/m_{\text{dm}}(\text{MeV}), \quad (5)$$

which is considerably longer than the age of the universe.

III. AXINO DECAY

Via R-parity violating couplings, axino LSPs may decay to Standard Model particles. The decay width for

such processes depends on the axion model and the nature of the R-parity violation considered.

There are two classes of invisible axion models, KSVZ [29] and DFSZ [30]. Both of these introduce at least one extra field, Φ , which breaks the Peccei-Quinn (PQ) symmetry at a high scale, f_a . Supersymmetric versions of these models give rise to two corresponding classes of axinos.

In the first of these scenarios (KSVZ), the field Φ couples to a pair of heavy quark states via the superpotential coupling, $W = \lambda \Phi Q \bar{Q}$. In the second scenario (DFSZ), Standard Model fermions carry PQ charge. However, they do not have direct couplings to the PQ field. The PQ field, however, couples to the Higgs sector which contains two Higgs doublets. In both scenarios, the axino has a gaugino-gauge boson coupling proportional to the PQ anomaly [21]

$$\begin{aligned} \mathcal{L}_{\tilde{a}\lambda A} = & i \frac{\alpha_Y C_{aYY}}{16\pi(f_a/N)} \tilde{a} \gamma_5 [\gamma^\mu, \gamma^\nu] \tilde{B} B_{\mu\nu} \\ & + i \frac{\alpha_s}{16\pi(f_a/N)} \tilde{a} \gamma_5 [\gamma^\mu, \gamma^\nu] \tilde{g}^b G_{\mu\nu}^b. \end{aligned} \quad (6)$$

C_{aYY} is a model dependent number of $\mathcal{O}(1)$.

We will be mainly interested in axino-fermion-sfermion couplings, in particular axino-lepton-slepton couplings, $g_{\tilde{a}l\tilde{l}}$, in both of those scenarios. In the KSVZ scenario, there is no direct coupling between the axino and Standard Model fields since they are not charged under $U(1)_{PQ}$. However, such an coupling could be induced at loop-level via a Bino- A_Y -lepton loop [22] as

$$|g_{\tilde{a}l\tilde{l}}| \propto \frac{\alpha_Y^2 C_{aYY}^2 M_1}{\pi^2 f_a} \log\left(\frac{f_a}{M_1}\right). \quad (7)$$

On the other hand, in the DFSZ scenario, since the axino has a higgsino component, there is going to be a direct coupling

$$|g_{\tilde{a}l\tilde{l}}| \sim g \frac{v}{f_a}, \quad (8)$$

where g is of the size of the gauge coupling suppressed by the mixing angle between higgsinos and gauginos. For our estimate, it is useful to pull out the common factor in $g_{\tilde{a}l\tilde{l}}$ (with the rough order of magnitude identification $v \sim M_1$ in mind) and write $g_{\tilde{a}l\tilde{l}} = \hat{g} v / f_a$. From Eq. 7 and Eq. 8, we can roughly estimate $\hat{g} \sim 10^{-2}$ in the DFSZ case and $\hat{g} \sim 10^{-4}$ in the KSVZ case.

The exact decay width depends on the details of the model, such as the Higgs potential and the spectrum and mixings of the superpartners. Rather than going into a detailed study, we give here an order-of-magnitude estimate. The axino life time is estimated to be

$$\begin{aligned} \tau_{\tilde{a}} \sim & 10^{20} \text{ sec} \times \left(\frac{10 \text{ MeV}}{m_{\tilde{a}}}\right)^5 \\ & \times \left(\frac{m_{\tilde{l}}}{\text{TeV}}\right)^4 \left(\frac{f_a}{10^{11} \text{ GeV}}\right)^2 \left(\frac{0.1}{\lambda}\right)^2 \hat{g}^{-2}. \end{aligned} \quad (9)$$

λ is the R-parity violating leptonic trilinear coupling which appears in the superpotential as $W = \lambda_{ijk} L_i L_j E_k^c$. Positrons could be produced in the decays $\tilde{a} \rightarrow \nu_\tau e^+ e^-$ or $\tilde{a} \rightarrow \nu_\mu e^+ e^-$ which result from the couplings λ_{311} and λ_{211} , respectively. λ_{211} is constrained by charge current universality as $\lambda_{211} \lesssim 0.1(m_{\tilde{e}_R}/200 \text{ GeV})$. λ_{311} is constrained by $\Gamma(\tau \rightarrow e \nu \bar{\nu})/\Gamma(\tau \rightarrow \mu \nu \bar{\nu})$ as $\lambda_{311} \lesssim 0.12(m_{\tilde{e}_R}/200 \text{ GeV})$. See Ref. [17] for details. For axinos with a mass in the range of 1-300 MeV, for a wide range of couplings it is possible to obtain the desired lifetime found in Eq. 5.

In addition to trilinear R-parity violating decays, bilinear couplings of the form $\mu_i L_i H_2$ could also contribute to the 511 keV gamma-ray production. The impact of this term on the axino lifetime was studied in Ref. [19]. This bilinear term induces mixing between higgsinos (and hence photinos) and neutrinos. Therefore, axinos can decay via $\tilde{a} \rightarrow \gamma + \nu$. μ_i is constrained by the diffuse gamma ray background to be $< \text{keV}$ [19]. In this case, the axino lifetime is about 10^{25} sec which is potentially interesting. However, since this decay produces $\gamma + \nu$ rather than positrons, this mode is useful for explaining the 511 keV line structure only if the mass of the axino is precisely 1022 keV. Such a scenario is indeed fine-tuned, although it is technically natural. Another potentially important mode induced by the bilinear coupling is $\tilde{a} \rightarrow \tau^+ + \pi^-$. However, it is kinematically forbidden for the range of axino masses we are interested in.

IV. DISCUSSION AND CONCLUSIONS

In this letter, we have demonstrated that a light axino (1-300 MeV), in either the KSVZ or DFSZ axion models, with trilinear R-parity violating couplings could be responsible for the 511 keV line emission observed from the galactic bulge. In this scenario, axinos constitute the major component of the cold dark matter and are present in the galactic halo with a cusped distribution ($\gamma \sim 1.2$).

At this time, we can not exclude the possibility that poorly understood conventional astrophysics is responsible for the observed positron production in the galactic bulge. To differentiate such a scenario from more exotic sources, such as light decaying particles, future tests must be made [31]. Additionally, if decaying axinos are the source of the 511 keV emission, signatures of supersymmetry, and R-parity violation will likely be observed at the LHC.

As this letter was being completed, an article appeared which also discussed decaying particles as the source of the observed 511 keV emission [32]. They considered decaying sterile neutrinos with rather constrained mixing parameters. They also discussed decaying scalars with gravitational strength interactions.

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